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ON ESTIMATING THE EFFECT OF ASIAN EARTHQUAKE CODAS ON THE EXPLOSION DETECTION CAPABILITY OF LASA

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13. ABSTRACT

A study was made of the short period detection characteristics of LASA within the codas of earthquakes occurring in the Kurile Islands region and near the Kamchatka peninsula. This study yielded an estimate of the time interval that LASA would not detect an explosion in central Asia following an earthquake in either of the two seismic regions; this estimate is given as a function of earthquake-explosion magnitude difference. An attempt was also made to model the hypothetical cases where the explosions were collocated with the earthquakes in either the Kuriles or Kamchatka regions and estimates of the mask time intervals are given for these cases. The results of the experiments are extended in order to estimate the total time, during the decade 1961-1972, that an explosion of a given magnitude in either central Asia, the Kuriles, or Kamchatka would have gone undetected at LASA due to the seismicity of the latter two regions. This total mask time, under various assumptions, is quantified into separate time intervals in the cases where the explosions and earthquakes are collocated. A result of this quantification is that, in the context of this experiment, there were a maximum of 300 two minute time intervals during the decade that a magnitude 5.0 explosion in the Kuriles might possibly have gone undetected at LASA, and 10 such intervals that the explosion most probably would have gone undetected, due to the seismicity of the Kurile Islands region.

14. KEY WORDS

earthquake codas	LASA	seismic discrimination
explosion detection	mask time	seismicity

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ON ESTIMATING THE EFFECT OF ASIAN EARTHQUAKE CODAS ON THE EXPLOSION DETECTION CAPABILITY OF LASA

J. R. FILSON

Group 22

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ABSTRACT

A study was made of the short period detection characteristics of LASA within the codas of earthquakes occurring in the Kurile Island region and near the Kamchatka peninsula. This study yielded an estimate of the time interval that LASA would not detect an explosion in central Asia following an earthquake in either of the two seismic regions; this estimate is given as a function of earthquake-explosion magnitude difference. An attempt was also made to model the hypothetical cases where the explosions were collocated with the earthquakes in either the Kuriles or Kamchatka regions and estimates of the mask time intervals are given for these cases. The results of the experiments are extended in order to estimate the total time, during the decade 1961-1972, that an explosion of a given magnitude in either central Asia, the Kuriles, or Kamchatka would have gone undetected at LASA due to the seismicity of the latter two regions. This total mask time, under various assumptions, is quantified into separate time intervals in the cases where the explosions and earthquakes are collocated. A result of this quantification is that, in the context of this experiment, there were a maximum of 300 two minute time intervals during the decade that a magnitude 5.0 explosion in the Kuriles might possibly have gone undetected at LASA, and 10 such intervals that the explosion most probably would have gone undetected, due to the seismicity of the Kurile Islands region.

Accepted for the Air Force
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Acting Chief, Lincoln Laboratory Liaison Office

INTRODUCTION

Consideration of a treaty banning the testing of nuclear weapons underground raises the question of the degree of deterioration, due to the natural seismicity of the earth, of the detection capability of a seismic station or network of stations. Little, if any, formal analysis of this problem exists in the literature of seismology. This report describes a study of a limited aspect of this topic. It attempts to answer the question: For how much total time during a decade would an explosion of a given size at any one of three Asian test sites go undetected at the Large Aperture Seismic Array (LASA) due to the seismicity of the Kurile Islands and the Kamchatka Peninsula?

No attempt was made here to solve the problem of explosion detection within earthquake codas, only to define the magnitude of the problem. Additionally, no attempt was made to address the problem of identification of the explosion once it has been detected. An effort was made to make the experiments as realistic as possible in that an existing detection scheme was applied to actual data.

In what follows the general approach to the problem is described, the details of the method are given, and the results of the experiment are set down. A section has been included which applies the results of this work to the problem of detecting clandestine explosions fired just after earthquakes for the purpose of detection evasion. This is somewhat an awkward topic since it requires discussion of detecting an act that might have possibly been agreed to as banned. Nevertheless the quantification of the risks of undetected violations is somewhat relevant to the discussion of a nuclear test ban agreement and such a quantification is considered here in a very limited and qualified sense. The chief qualification is that this study is limited to the use of one seismic array, LASA; how the results based on this lone station will scale to a global network is not considered here.

Thus the methods and arguments presented below may merit some general consideration, the numbers that come out of these processes are by no means definitive in the sense of world wide seismicity and seismic monitoring networks.

METHOD

In this section the method, that was used to estimate the total period of time that an explosion of a given magnitude would have gone undetected at LASA due to the seismicity of a given region, is set down. Let the functions M, E, and τ, be defined as follows:

$M(m_q, T, s_2)$ — The number of earthquakes of magnitude m_q that occurred in the region s_2 over the period of time T,

$E(m_q - m_x, s_1, s_2)$ — an estimate of the time that an explosion of magnitude m_x at site s_1 would go undetected at LASA in the P wave coda of an earthquake of magnitude m_q from region s_2, and

$\tau(m_x, T, s_1, s_2)$ — an estimate of the total mask time that an explosion of magntiude m_x at site s_1 would have gone undetected at LASA due to the natural seismicity of region s_2 over the period of time T.

The assertion is made that the total mask time τ may be represented as

$$\tau(m_x, T, s_1, s_2) = \Sigma M(m_q, T, s_2) E(m_q - m_x, s_1, s_2) \qquad (1)$$

where the summation is over some range of m_q. Surely at some low value of m_x an explosion of that magnitude would never be detected due to the ambient seismic noise in the earth. All explosions at some higher value of m_x would be detected if it were not for the natural seismicity of the earth. Equation (1) can be used to estimate the effect of this natural seismicity on the ability of LASA to detect these

higher magnitude explosions.

The chief difficulty met in attempting to use equation (1) lay in the determination of the function E. This function is called a failure function since it represents an estimate of the amount of time LASA failed to detect an explosion, in the coda of an earthquake, given an earthquake-explosion magnitude difference. Briefly, the scheme used here to estimate E was as follows. The short period waveform of the LASA beam from a presumed explosion was scaled to various magnitudes and repeatedly added to the coda of a beam formed using the short period data of an earthquake. The earthquake beam was always aimed at the presumed explosion site in order to enhance the explosion signal with respect to the earthquake coda. Knowing the earthquake magnitude m_q, the scaled explosion magnitude m_x, and the number of scaled explosions repeatedly added to the earthquake coda every t_o seconds; the number (N) of these explosions that were missed, by some standard detection scheme, was determined. By repeating the process, using other earthquake data and scaling the explosion waveform to other magnitudes, a suite of measurements of N were made as a function of m_q-m_x. This allowed an estimation of the function E using

$$E(m_q - m_x, s_1, s_2) = t_o \cdot N(m_q - m_x, s_1, s_2) \tag{2}$$

Of course $N(m_q - m_x, s_1, s_2)$ was not found to be constant for an explosion of magnitude m_x at site s_1 and all earthquakes of magnitude m_q within region s_2. Although N increased with the difference m_q-m_x, the scatter about any specific value of the difference was considerable. This was probably due to the variance in coda shape and duration between earthquakes from the same region. As will be seen however, the maximum number of explosions missed, N_{max}, was fairly well defined and could be represented by an expoential function as

$$N_{max} = \delta \exp[\xi (m_q - m_x)]. \qquad (3)$$

Thus an estimate of the maximum detection failure time at LASA, of an explosion of magnitude m_x at site s_1 due to an earthquake of magnitude m_q at site s_2, is

$$E_{max}(m_q - m_x, s_1, s_2) = t_o \cdot N_{max}, \qquad (4)$$

where t_o is the interval between the explosion waveforms. In practice, the equation used to estimate the maximum total time, τ_{max}, that an explosion of magnitude m_x at site s_1 would have gone undetected at LASA due to the natural seismicity of region s_2 over the time period T was

$$\tau_{max}(m_x, T, s_1, s_2) = \sum_{m_q} M(m_q, T, s_2)\, t_o\, N_{max}(m_q - m_x, s_1, s_2)\,. \qquad (5)$$

where N_{max} was computed from (3).

In this study an attempt was made to estimate $\tau_{max}(m_x, T, s_1, s_2)$ for the following four cases.

Case I	s_1	-	presumed Soviet test site (STS) Semipalatinsk, Kazakh
	s_2	-	Kurile Islands region
Case II	s_1	-	STS
	s_2	-	Kamchatka Peninsula region
Case III	s_1	-	hypothetical test site in the Kurile Islands
	s_2	-	Kurile Islands region

Case IV s_1 - Hypothetical test site on the Kamchatka Peninsula

s_2 - Kamchatka Peninsula region.

The magnitude range of m_q was taken to be 4.0 - 7.1 and the time T to be the decade 1963-1972.

Cases I and II are not contrived; presumably explosions are detonated at the Semipalatinsk site and it is acceptable to add these signals to the earthquake codas in order to effect the detection experiments. The contrived cases, III and IV, are justified in that they represent the extreme instances where the explosion and the earthquake are collocated. Here the explosion detection beam must be steered directly at the interfering earthquake signal, thus minimum earthquake coda attenuation due to beamforming is expected.

DETAILS OF THE EXPERIMENT

The following event was taken as a typical explosion from STS; the parameters were given by the U.S. Coast and Geodetic Survey (USCGS):

Date	-	5 September 1968
Origin time	-	$04^h05^m57.4^s$
Latitude	-	49.8° North
Longitude	-	78.1° East
Depth	-	0.0 kms (fixed)
Magnitude	-	5.5 based on 24 observations.

The appropriate LASA beam trace was formed and this trace was scaled to ten other magnitudes (m_x) through division by the following factors (f):

f	m_x	f	m_x
1	5.5	20.	4.2
2	5.2	32.	4.0
3.2	5.0	50.	3.8
5.0	4.8	80.	3.6
8.0	4.6	125.	3.4
12.5	4.4		

Before scaling the original explosion beam trace was filtered using a third order band pass filter with 3 db corners at .9 and 1.4 Hz. The filter is used routinely in the LASA detection scheme.[1]. Figure 1 shows the unfiltered and filtered versions of the explosion beam trace, sampled 10 times a second and repeated every 20 seconds.

The array data for the various earthquakes was then phased using delays appropriate for the proposed explosion site and summed. This earthquake beam was

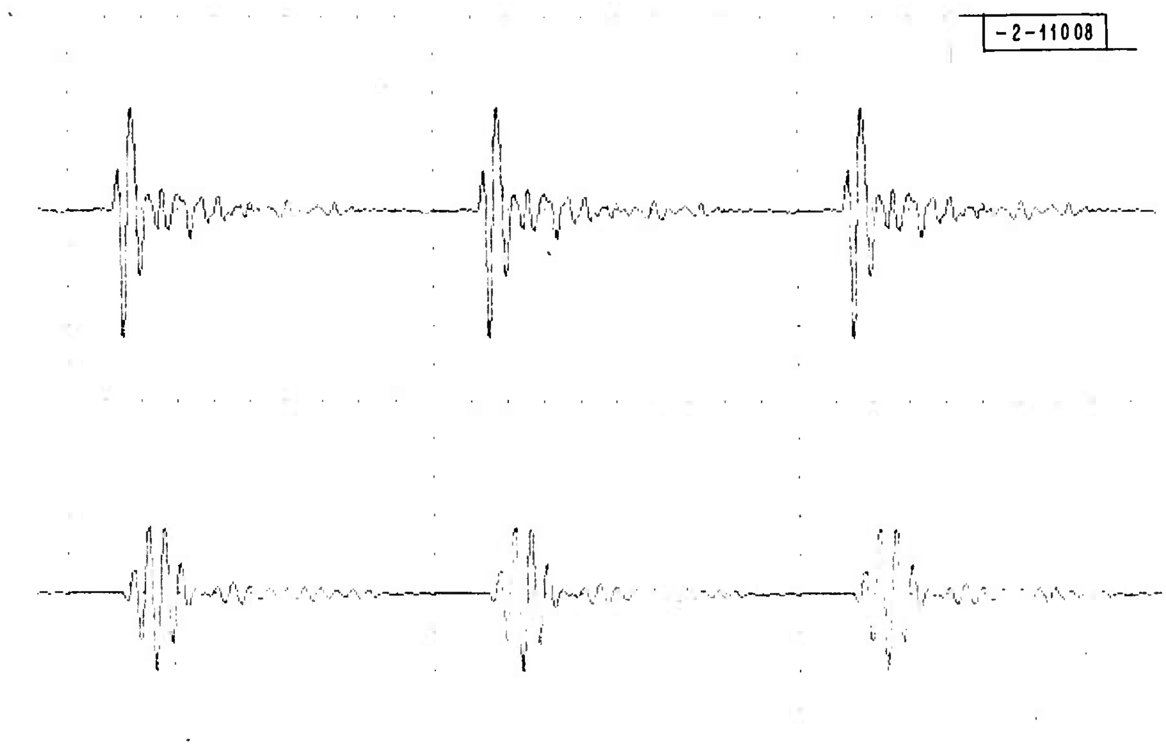

Fig. 1. The traces of the short period LASA beam showing the P wave from a presumed explosion in eastern Kazakh, S.S.R. The trace is repeated every 20 seconds as are the vertical dotted lines. The lower trace resulted in band-pass filtering the unfiltered upper trace. Scaled versions of the lower trace were added to filtered earthquake codas in order to perform the detection experiments described in the text.

filtered using the same filter described in the last paragraph. The filtered earthquake beam was then added to the repeated filtered explosion beam trace for use in the detection study.

In Cases I and II this procedure is straightforward and somewhat realistic. Cases III and IV are less so in that there are no known large underground explosions in the Kuriles or Kamchatka region. In these cases the same STS explosion beams were used as in Cases I and II, however the earthquake beams were formed on hypothetical sites in the Kuriles and Kamchatka regions. This is equivalent to asserting that, at LASA, the short period P waves from an explosion in far, northeastern Asia will be similar to one in central Asia. Because of geologic contrasts between the actual and hypothetical explosion sites this assertion is questionable but the ruse is necessary to form such experiments. The locations of the explosions and earthquakes for the various cases are summarized below:

	Explosion	Earthquakes
Case I	50°N 78°E	40-50°N, 145-155°E
Case II	50°N 78°E	50-60°N, 155-170°E
Case III	45°N 150°E	40-50°N, 145-155°E
Case IV	55°N 160°E	50-60°N, 155-170°E

The explosions were all taken to be at the surface and no subdivision of the earthquake population with respect to depth was attempted. A complete list of the earthquakes used to estimate the function $N(m_q - m_x, s_1, s_2)$ is given in the Appendix. The earthquake regions given above are also those used to compute the seismicity function $M(m_q, T, s_2)$ from USCGS seismicity lists for the decade 1963-1972.

The detection scheme now remains to be described. The scheme was modeled after that used at the Seismic Array Analysis Center (SAAC) and is described in the reference.[1] Basically the method compares the ratio of a short term rectified signal average to a similar long term average and declares a detection when then ratio exceeds a certain threshold for a given number of comparisons. No search was made to find an optimum coda detection process; a standard process was used with threshold parameters that gave relatively few false alarms.

The short term average (STA) was computed using the following formula from reference 1,

$$\mathrm{STA}(n\Delta t) = \frac{1}{P} \sum_{p=0}^{P-1} \left| B[(n-p)\Delta t] \right| . \tag{6}$$

Here $B[n\Delta t]$ represents the filtered beam sampled at $n\Delta t$. In practice Δt was set at .2 sec and P=3, i.e. the STA was computed every .6 sec. The long term average (LTA) was computed using the current STA value, STA_n, and the last LTA value, LTA_{n-1}, and the recursive relation

$$\mathrm{LTA}_n = 2^{-\eta}\mathrm{STA}_n + (1-2^{-\sigma})\,\mathrm{LTA}_{n-1} . \tag{7}$$

In practice values for η and σ were 1. and 4. respectively.

Because the effective length of this LTA was greater than the 20 sec interval at which the explosions were added, the LTA was computed using the filtered earthquake beam to which no explosion traces had been added. This means that the added explosions did not contaminate the LTA upon which the detections were based. Eleven STA values were computed for the respective scaled explosion-earthquake sum traces and also, to check false alarms, on the earthquake trace alone. Thus, 12 STA/LTA ratios

were computed every .6 sec, one on the earthquake trace and one on each of the 11 earthquake traces to which explosions scaled to 11 different magnitudes were added every 20 seconds. A detection was declared on any of the twelve traces when the STA/LTA ratio exceeded 10 db for 1.8 seconds, i.e. for three consecutive STA/LTA measurements.

An example of the method and the performance of the detection scheme is shown by Figure 2 where earthquake number 15 is shown under the conditions of Case III. The top three traces are the earthquake trace plotted at different gain levels. Traces 4 and 5, with explosions equivalent to magnitudes 5.5 and 5.2 added, are plotted at the same gain as trace 1. Traces 6 and 7, explosion magnitudes 5.0 and 4.8, are plotted at the gain of trace 2 and traces 8 and 9, explosion magnitudes 4.6 and 4.4, at the gain of trace 3. Explosion declared detections are marked with an "X", undetected explosions are marked with an "O". This writer feels that, in the light of such examples, the detection criteria used were reasonable ones however the reader must make his own judgement. One other point bears mention at this stage. As it turned out in most runs of the experiment the explosions were added such that one usually fell a few seconds before the beginning of the earthquake arrival. This will tend to minimize the number of explosions missed but this feature should be balanced when the failure function is selected to represent the maximum number of explosions undetected.

The remaining details of the experiment are simply described. The detection criterion was applied to the earthquake and the 11 earthquake plus explosion traces. The number of false alarms was recorded from the former, the number of explosions missed from the latter. If the number of detected explosions fell below the number of explosions added before the earthquake signal, due to high noise conditions, that trace was disregarded. Otherwise the number of explosions missed was plotted against the magnitude

difference between the earthquake and the scaled explosion and the failure function for each case was established.

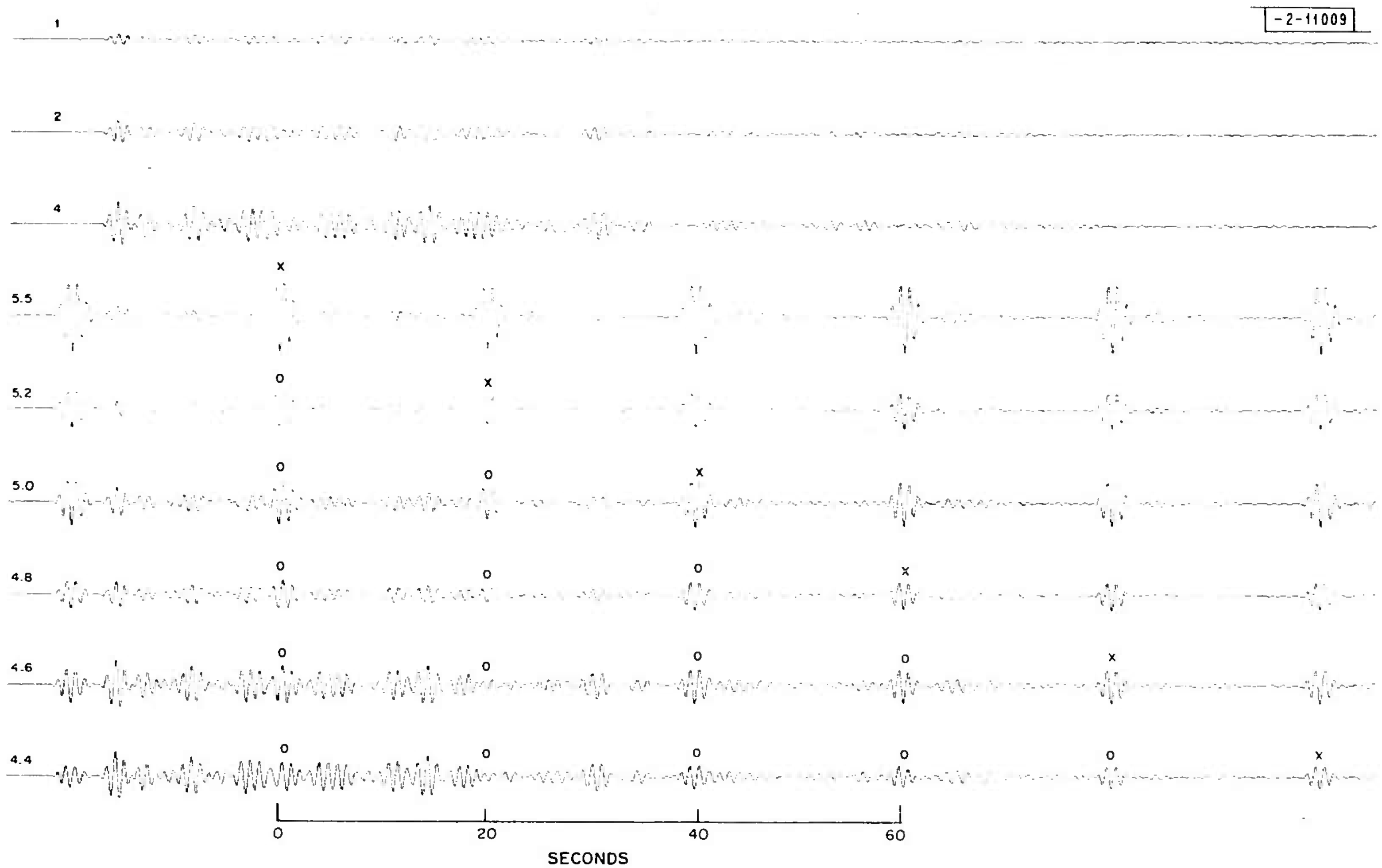

Fig. 2. An example of the result of adding explosion traces to an earthquake coda. The top three traces represent the filtered beam from earthquake number 15, Case III. It is shown at three gain levels, 1, 2, and 4. The lower six traces show explosions of magnitude 5.5 and 5.2 added to the earthquake and shown at gain 1; explosions of magnitude 5.0 and 4.8 added to the earthquake, gain 2; and explosions of magnitude 4.6 and 4.4 added to the earthquake, gain 4. The first explosion detected following the earthquake is marked by an "X". Undetected explosions are marked by "O".

RESULTS OF THE EXPERIMENT

The number of explosions undetected by the method just described are plotted versus the earthquake-explosion difference in Figures 3-6 for Cases I-IV respectively. The straight lines drawn on these figures represent the author's estimate of the maximum number of explosions that would be missed for a given magnitude difference in each case. The parameters of these lines, which are in the form of equation (3), are

Case	δ	ξ
I	1.9	1.66
II	2.9	1.64
III	4.5	1.20
IV	5.5	1.26.

The distribution of points and the parameters of the straight lines on these figures merit some discussion. Although Cases I and II (Figures 3 and 4) are similar in that the explosions are from the same site and the earthquakes are from regions contiguous to each other, the scatter of the points is greater in Case II than in I. The earthquakes used in Case I (Kurile Islands) all occurred within a two month period at nearly the same location (43N 147E) while those of Case II (Kamchatka) are more widely dispersed in time and space. Thus, although the lines on the two figures have about the same slope (ξ) the zero intercepts (δ) vary by 1.0. The same observation arises when the maximum failure lines on Figures 5 and 6 are compared. It is also of interest to compare the trend of the points in Cases I and II with that of III and IV. The former appear to exhibit a steeper slope which is reflected in a higher value of ξ in the maximum failure lines drawn for Cases I and II than in III and IV. The slope or trend of these lines is largely controlled by the number of missed detections at high magnitude dif-

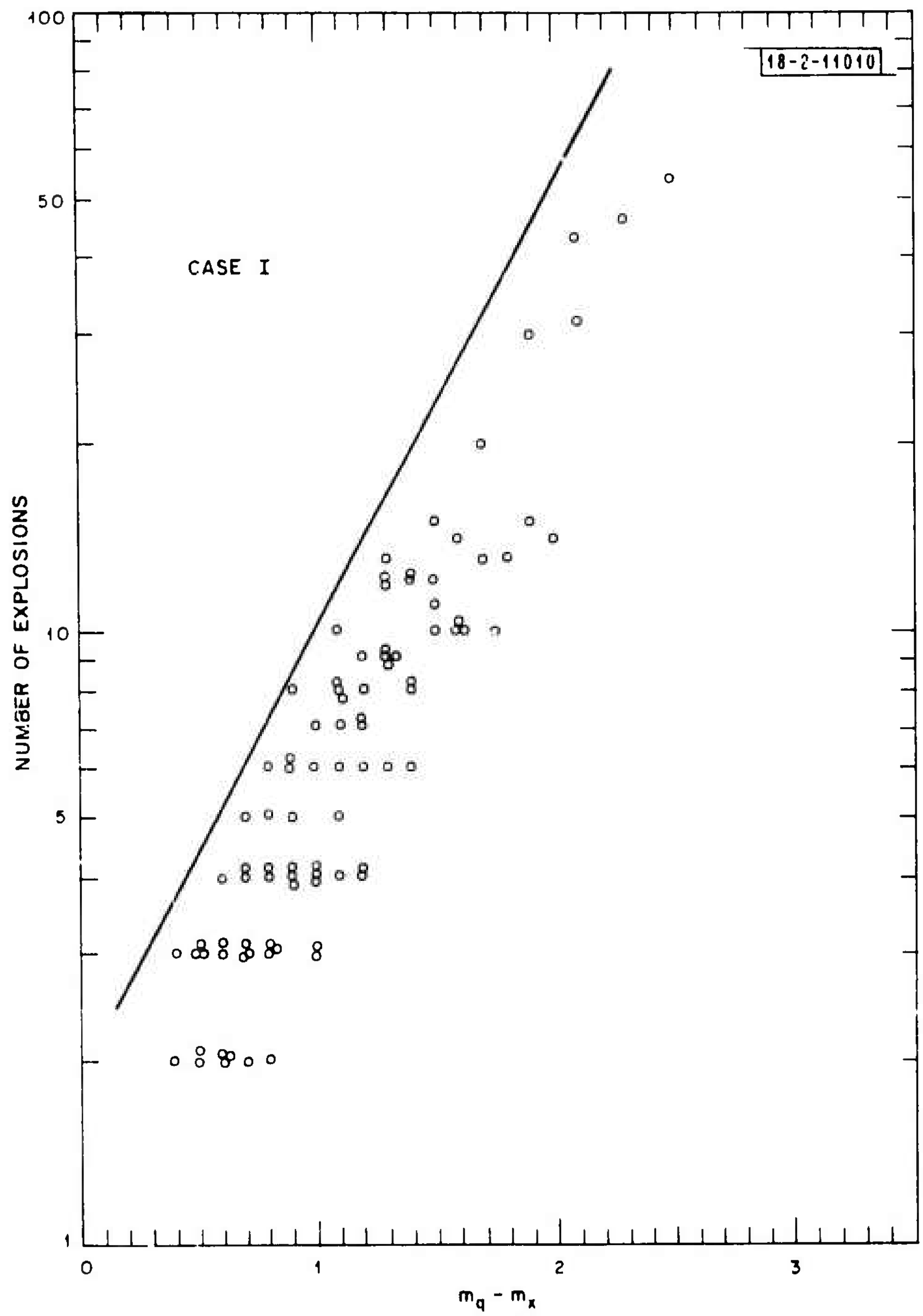

Fig. 3. The points represent the number of STS explosions undetected on the LASA beam, aimed at STS, due to Kurile Islands earthquakes. These points are plotted versus the magnitude difference ($m_q - m_x$) between the earthquake (m_q) and the explosion (m_x). This figure is relevant to Case I described in the text. The straight line represents the author's estimate of the maximum number of explosions missed as a function of magnitude difference. The explosions were added at 20 second intervals.

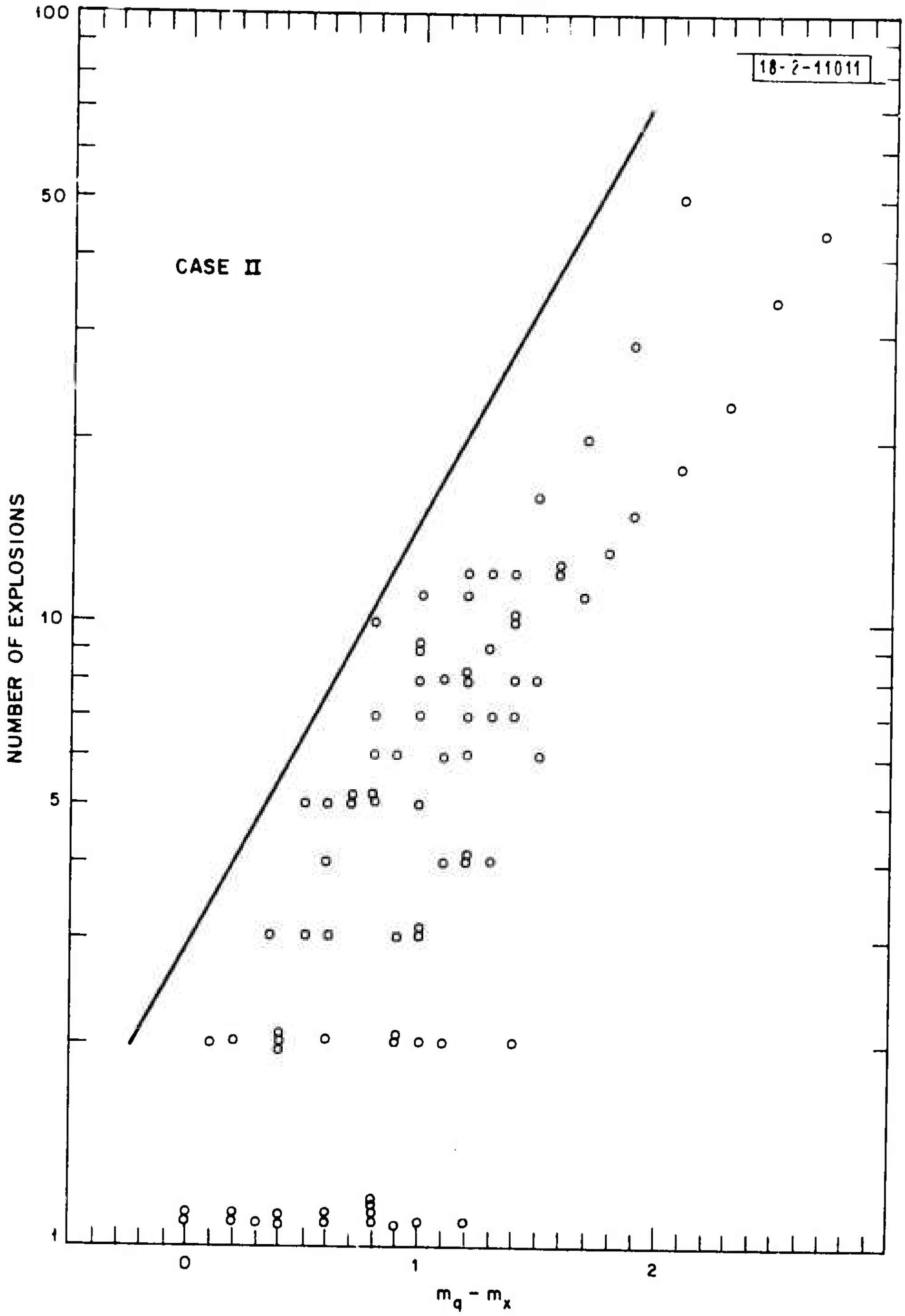

Fig. 4. A diagram analogous to Fig. 3 and relevant to Case II. STS explosions undetected on the LASA beam aimed at STS due to Kamchatka earthquakes.

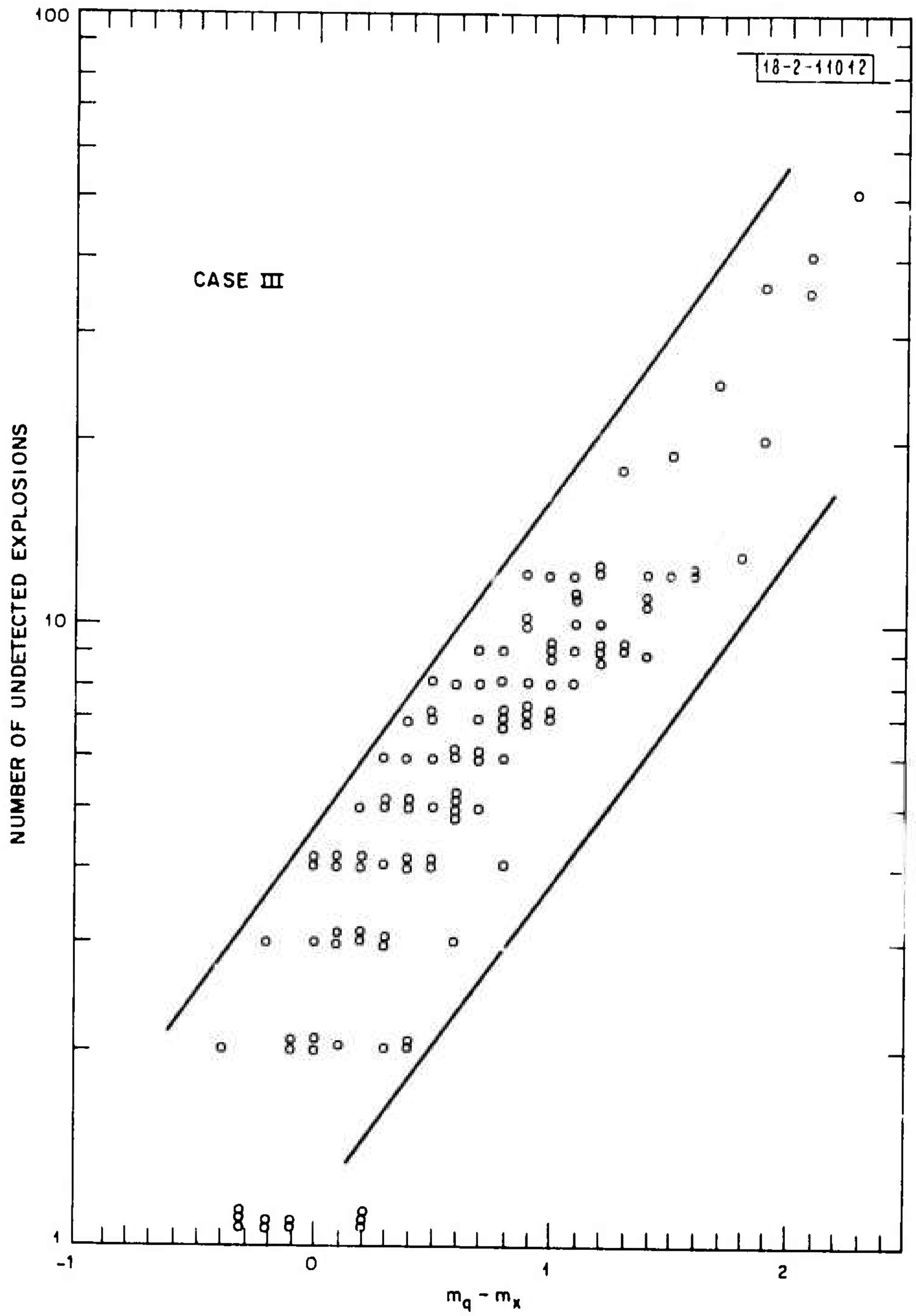

Fig. 5. A diagram analogous to Fig. 3 and relevant to Case III. Hypothetical Kuriles explosions undetected on the LASA beam aimed at the Kurile Islands due to Kurile Islands earthquakes.

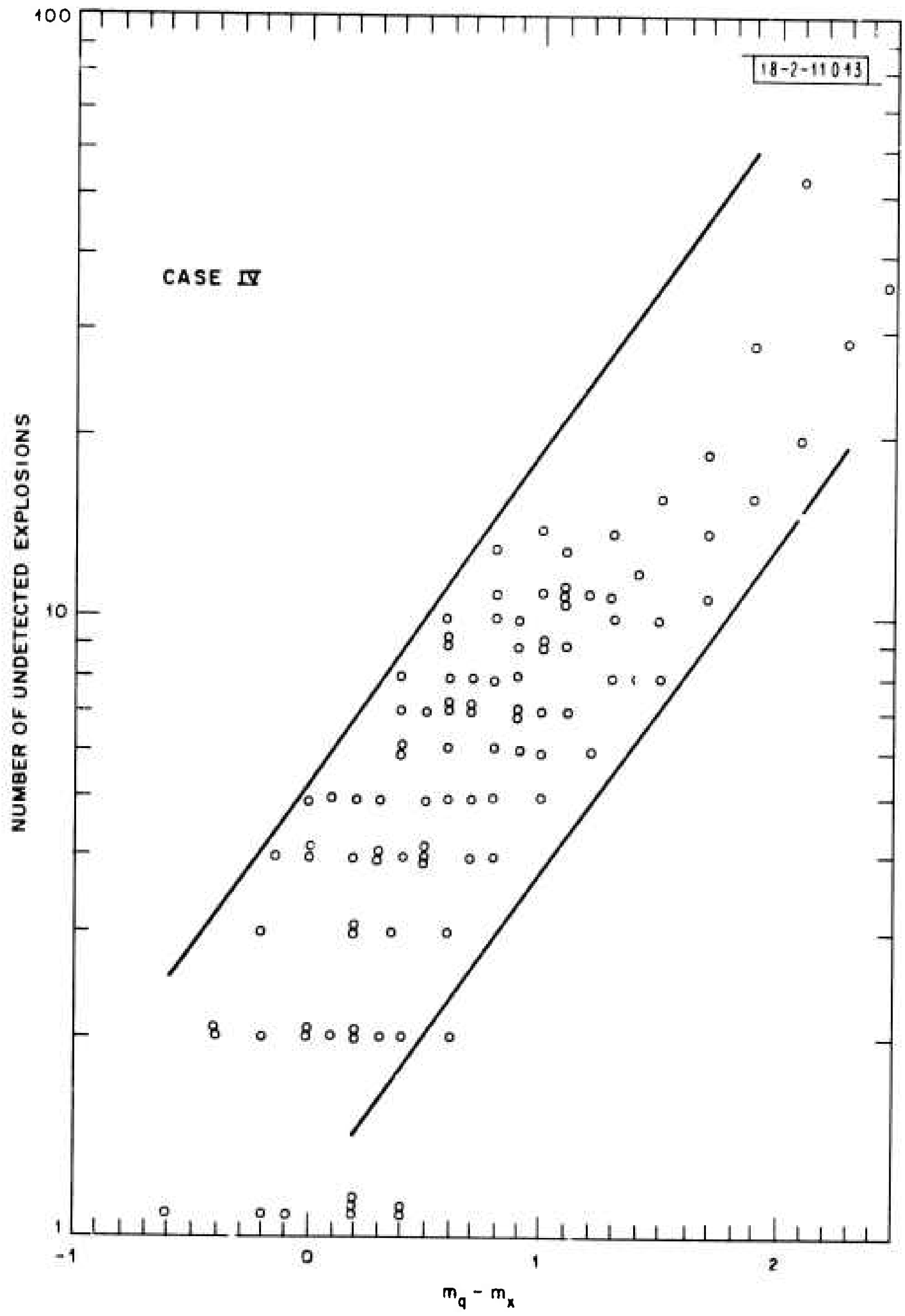

Fig. 6. A diagram analogous to Fig. 3 and relevant to Case IV. Hypothetical Kamchatka explosions undetected on the LASA beam aimed at Kamchatka due to Kamchatka earthquakes.

ferences, determined far back in the coda of the larger earthquakes. This leads to the conclusion that the coda from large events becomes increasingly incoherent with increasing time after the first arrival. Alternatively stated, the effectiveness of beamforming on location A to suppress the coda of an event from location B decreases with time after the arrival of the initial P wave from location B.

An attempt was now made to extend these results to estimate the maximum total time that an explosion of a given magnitude would have gone undetected at LASA due to the long term seismicity of two regions considered. This was done through equation (5). Before discussing the results of these calculations however, several qualifying comments should be made concerning their interpretation. The use of equation (5) requires an accurate knowledge of the seismicity of a region. Here USCGS lists have been used simply because they appear to be themost consistent source of seismicity information. Figures 7 and 8 show a cummulative number of earthquakes as a function of magnitude over the decade 1963-1972 for the Kurile Islands and Kamchatka regions respectively. It is clear from the flattening of these seismicity curves near magnitude 4.0 that this magnitude approximates the lower limit of sensitivity for the network of stations used by the USCGS to locate and assign magnitudes to seismic events from these regions. At what magnitude any flattening due to insensitivity and not nature begins, is the crucial yet undeterminable point. In Figure 7 a slight bend in the cummulative curve is seen at about magnitude 5.4, this seems too high to be due to network insensitivity which might be expected to become significant below magnitude 5.0. In any case, this effect must qualify any conclusion based on equation (1) at lower explosion magnitudes.

There exists a more specific qualification that may be placed on any result

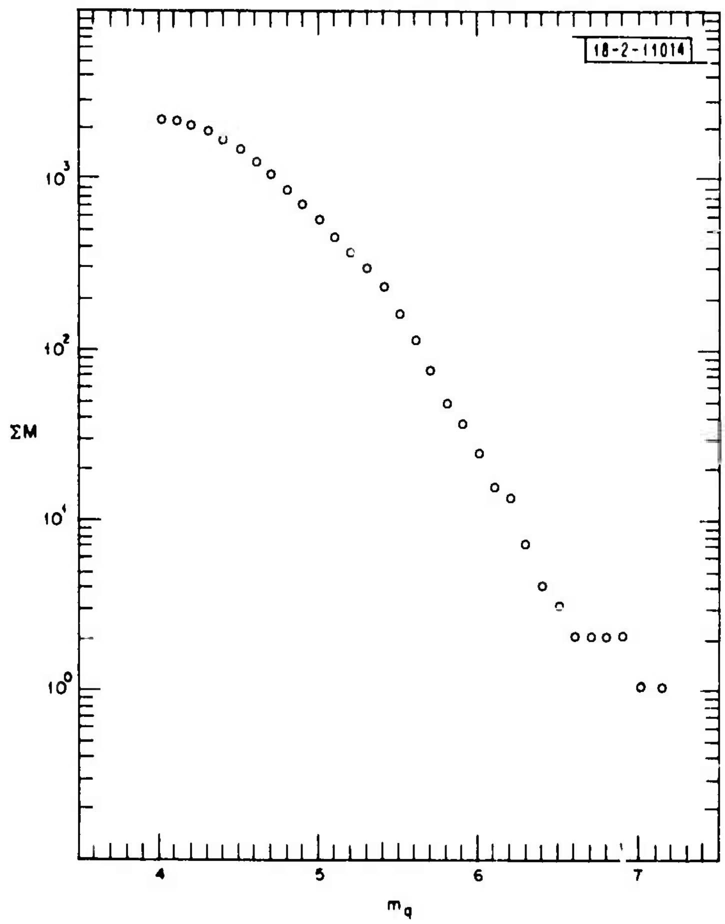

Fig. 7. The points represent the total number of earthquakes of a given magnitude (m_q) or greater reported by the USCGS during 1963-1972 as occurring in the Kurile Island region 40-50°N, 145-155°E.

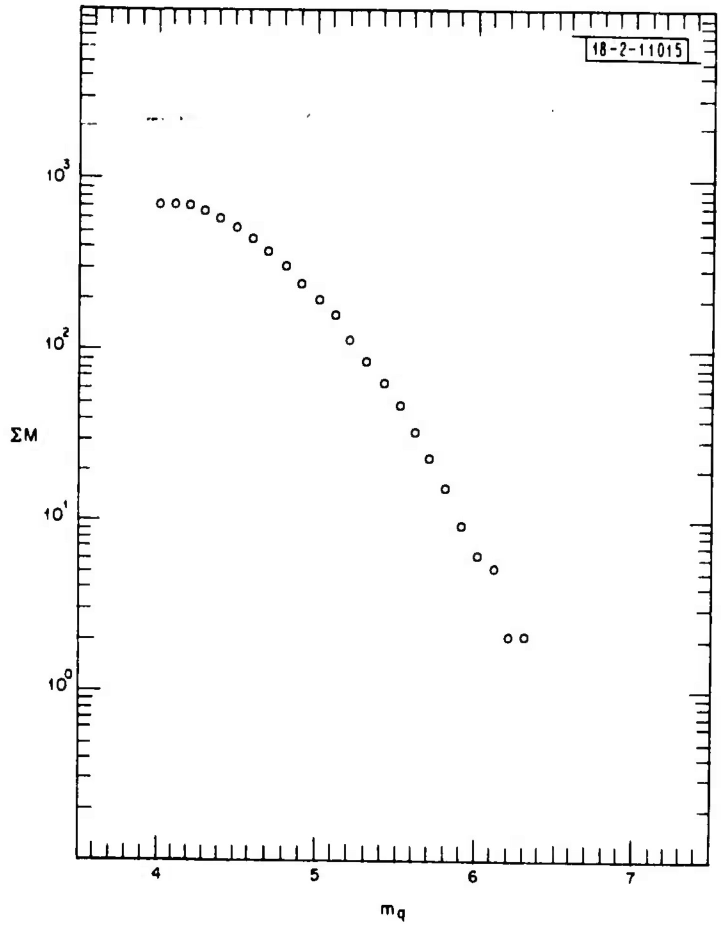

Fig. 8. The points represent the total number of earthquakes of a given magnitude (m_q) or greater reported by the USCGS during the 1963-1972 as occurring in the Kamchatka region 50-60°N, 155-170°E.

gained from the use of equation (5). Because of the form given the failure function by equation (3), the values assigned to its parameters, and the detection criteria used; an explosion may be hidden by an earthquake of smaller magnitude. Thus, in order to estimate the total time that a magnitude 4.0 explosion would be hidden, the total number of magnitude 3.8 earthquakes is required. Since earthquakes of magnitude 3.8 are not considered, any estimate of τ in this case must be low. The severity of this effect increases with the value of the parameter δ. In the summation of equation (5) all fractional detections have been rounded down to the nearest integer. This is a fairly safe procedure because all of the points of Figures 3-6 lie at least one unit below the maximum failure lines. In the light of the above discussion the condition that

$$\delta \exp[\xi(m_x - m_q')] < 1.0 \tag{8}$$

when estimating τ_{max}, where m_q' is the magnitude above which $M(m_q, T, s_2)$ is believed to be complete, assures the validity of the estimate τ in the context of equation (5).

Figures 9-12 show the results of applying the failure function for Cases I-IV to the appropriate 10 year seismicity data. The ordinate in these figures is the estimate of the maximum total time in minutes during the 10 year period that an explosion of magnitude m_x, at the site indicated, would have gone undetected due to the seismicity of either the Kurile Islands or the Kamchatka Peninsula. The arrows on these figures indicate an m_x below which the estimates are not strictly valid because of the problems discussed in the last two paragraphs. The placing of this arrow is based on the condition of equation (8) where $m_q' = 4.5$. This implies that the seismicity data of Figures 7 and 8 is considered complete down to $m_q = 4.5$. If the reader chooses to pick an alternate value for m_q' the arrows on Figures 9-12 will simply be shifted to the right or left

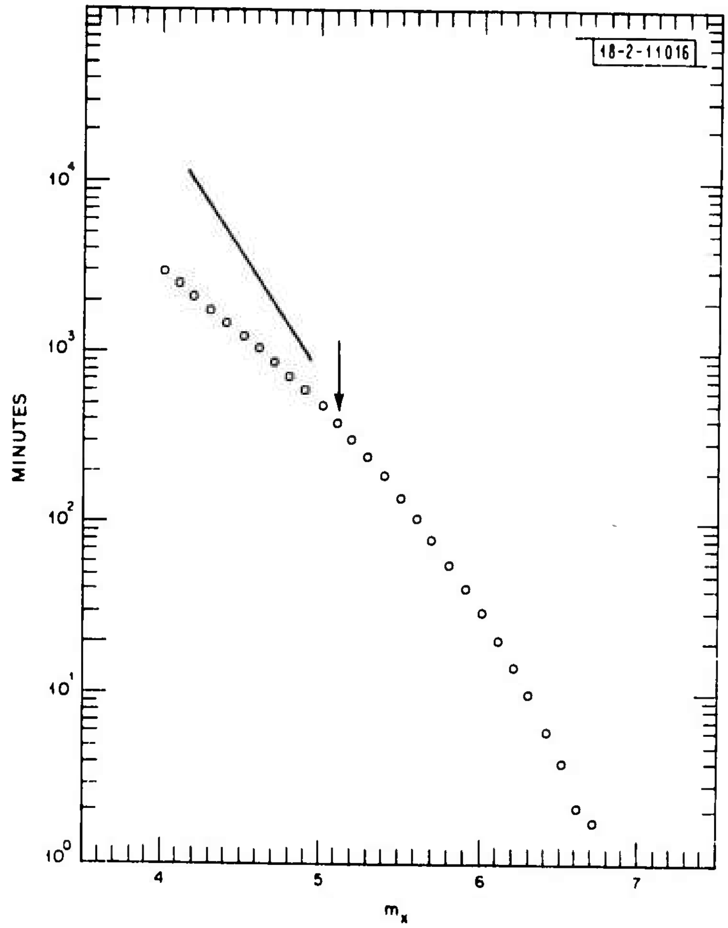

Fig. 9. The result of applying Eq. (1) to the data of Figs. 3 and 7 (Case I). The points represent an estimate of the time (in minutes) that a magnitude M_x explosion at STS would have gone undetected by LASA due to Kurile Island seismicity during the decade 1963-1972. The arrow represents the magnitude below which the results are not considered strictly valid. The line represents the approximate linear extension of the points at magnitudes greater than that of the arrow.

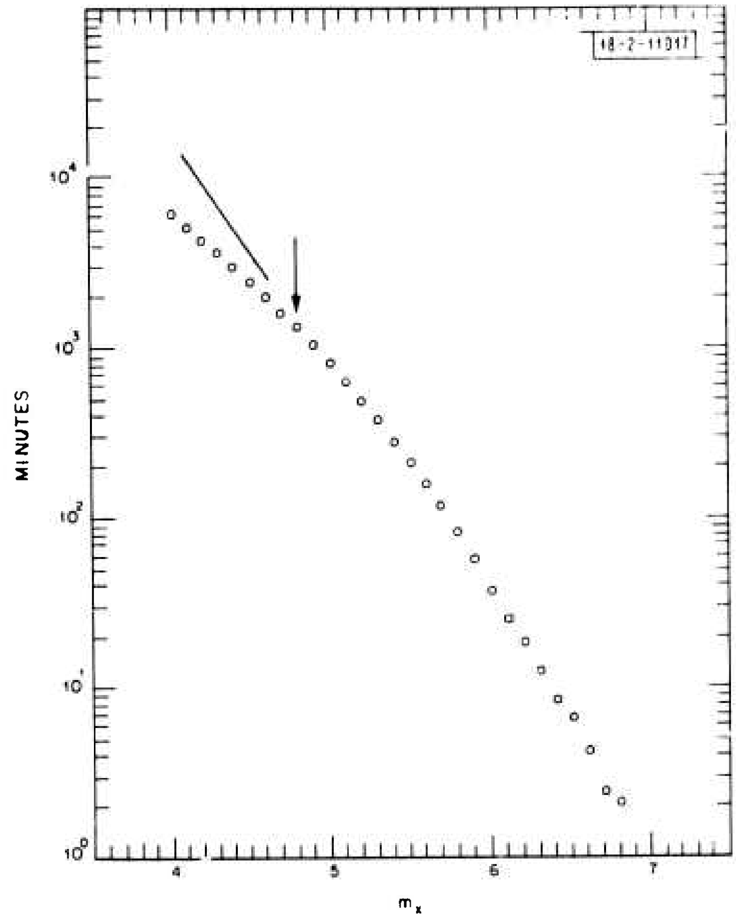

Fig. 10. A diagram analogous to Fig. 9 and relevant to Case II. The points represent an estimate of the time (in minutes) that a magnitude m_x explosion would have gone undetected by LASA due to Kamchatka seismicity during the decade 1963-1972.

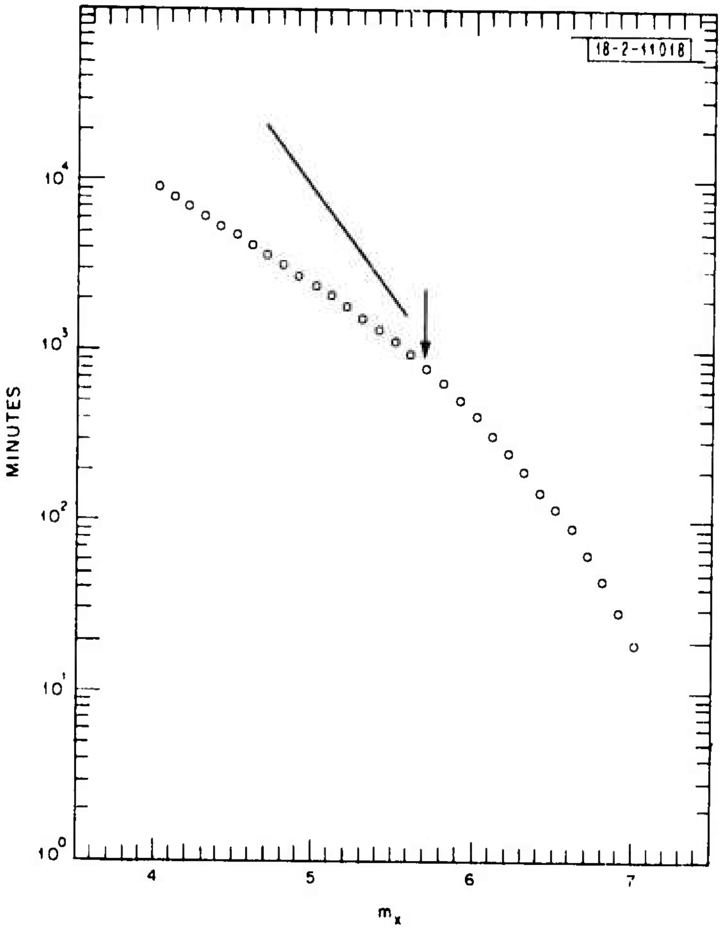

Fig. 11. A diagram analogous to Fig. 9 and relevant to Case III. The points represent an estimate of the time (in minutes) that a hypothetical, magnitude m_x explosion in the Kurile Islands would have gone undetected by LASA due to Kurile Islands seismicity during the decade 1963-1972.

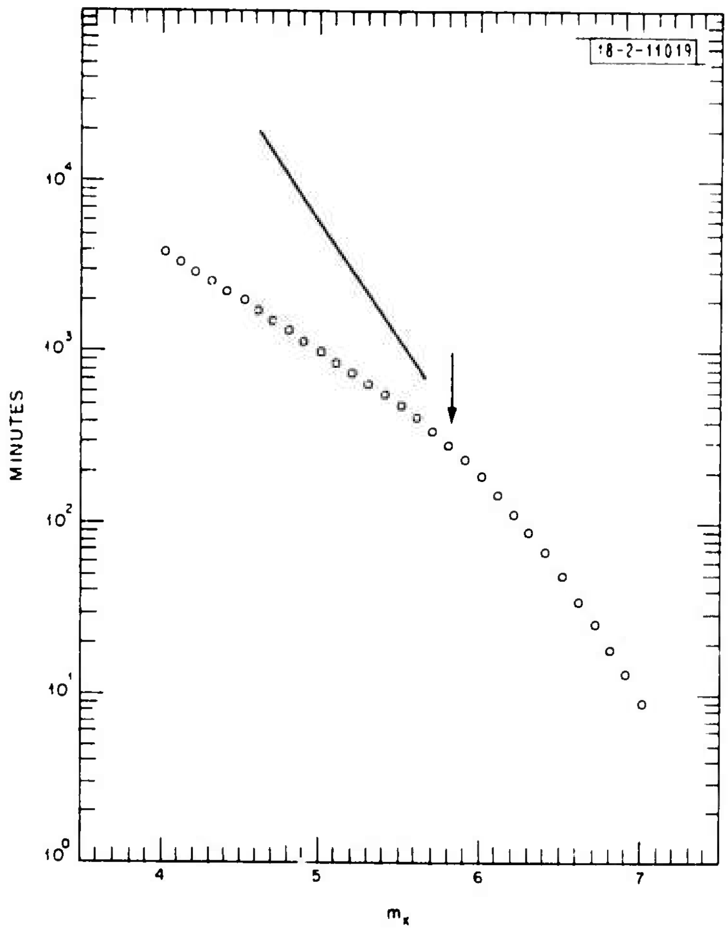

Fig. 12. A diagram analogous to Fig. 9 and relevant to Case IV. The points represent an estimate of the time (in minutes) that a hypothetical explosion of magnitude m_x near the Kamchatka Peninsula would have gone undetected by LASA due to Kamchatka seismicity during the decade 1963-1972.

the number of magnitude units that the new m_q' differs from 4.5. The straight solid lines on Figures 9-12 represent the author's approximation of the linear extention of the valid points to the right of the arrows to m_x values to the left of the arrows where the points shown are surely low.

As an example, these figures allow us to estimate the maximum total time that an explosion of say magnitude 5.5 would have gone undetected at LASA during the ten year period for each of the four cases. These results are summarized below:

Case	Total mask time
I	205 min (3.4 hrs)
II	135 min (2.3 hrs)
III	approx 2000 min (33.4 hrs)
IV	approx 100 min (16.7 hrs)

Again these are estimates of themaximum total mask time at LASA relevant only to the cases indicated. The maximum total mask time due to world wide seismicity would of course be greater.

The application of the detection scheme to the earthquake trace alone gave rise to nine false alarms in all of earthquake codas processed. Of the spurious detections, five were due to the surface reflection phase pP, two were due to a small interfering event, and the remaining two were genuine false alarms. This means that twice the nature of the earthquake coda was such that the detection method mistook it for a discrete, second seismic event.

EVASION

The results shown above permit some discussion of the problem of detecting an explosion deliberately hidden in an earthquake coda for the purpose of evasion. It is clear from Figures 9-12 that, in the case of LASA, the chances of success of such a scheme will increase as the distance between the explosion site and the masking earthquake location decreases. This is due to the earthquake coda attenuation on the array beam when steered at an explosion in a different region. In the cases studied here, it was found that when the explosion and earthquake locations, at about the same distance, were separated in azimuth by about 50° with respect to the array; the total explosion mask time was about an order of magnitude less than when the two source types were collocated. If one considers a global network of stations the chances of successfully hiding an explosion in the coda of a distant earthquake become even less. In order to avoid detection on a global network the clandestine test would have to be fired at a time such that the explosion P wave would not arrive before the earthquake P wave at any point on the surface of the earth. The way to ensure this would be to detonate the explosion upon arrival of the earthquake P wave at the explosion test site. If the masking earthquake were at say 50° distance from the explosion site, this would require waiting some 9 minutes after the origin time of the earthquake. At an array at teleseismic and equal distances from both explosion and earthquake sites the explosion P wave would arrive 9 minutes into the earthquake coda. Obviously this effect greatly reduces the chances of success of such a scheme.

Thus any potential evasion scheme would be more likely to succeed if the clandestine explosion was detonated within a region of high seismicity. Such a situation is considered here in Cases III and IV. In order to hide an explosion in a local earth-

quake one would require the means to detect, locate, and fire the explosion within a given time interval. Of course, the larger the earthquake the larger the explosion that could be hidden or, for a given explosion size, the longer the time interval available for seismic and engineering pre-firing routines. Thus, it is important in any evasion study not only to know the total time that an explosion of a given magnitude might be missed but also the quantization of this time. The proper quantization is considered to be the number of time intervals of a given length available, over an extended period of time, for the hiding of an explosion of a given magnitude. An attempt toward this quanitization, using LASA as the sole detector, has been made for Cases III and IV based on the detection data of Figures 5 and 6 and the seismicity data of Figures 7 and 8.

There is one point that must be considered at this time before such an attempt is made. The upper lines on Figures 5 and 6 represent, at least, the maximum number of explosions missed in the detection experiments. In every case fewer explosions went undetected at LASA than these lines indicate. An evasion scheme, using firing time intervals based on these lines, would have a high risk of detection at LASA since LASA always did better than the estimates these lines represent. To ensure success, with respect to LASA, a potential evasion scheme must be based on the minimum number of explosions missed at LASA for a given earthquake-explosion magnitude difference. The question is not then: What were the number of t minute time intervals that an explosion of magnitude m_x in the Kurile Islands might have gone undetected by LASA?; but rather: What are the number of these intervals that this explosion surely would have gone undetected at LASA. In order to estimate the number and length of these latter intervals using Figures 5 and 6, the lower lines that represent the minimum number of explosions missed must be used.

These minimum failure lines have been drawn parallel to the maximum failure lines but shifted down by about a factor of 4. The parameters of these minimum failure lines are

Case	δ	ξ
III	1.1	1.20
IV	1.1	1.26

The pairs of these lines have been used to estimate the number of separate time intervals of a given length (taken to the nearest minute) during 1963-1972 than a magnitude 5.0 explosion near either Kamchatka or the Kurile Islands might possibly (based on the maximum failure line) and most probably would (based on the minimum failure line) have gone undetected at LASA due to the seismicity of the two regions. The results are shown in Figures 13 and 14. Due to Kurile Islands earthquakes during the decade there were approximately 300 two minute intervals within which a magnitude 5.0 explosion in the Kuriles might have gone undetected at LASA, however if the explosion had been fired within each interval many would have been detected. There were approximately 10 two minute intervals within which the same explosion would surely have gone undetected at LASA. The respective number of two minute intervals for the Kamchatka region are approximately 130 and 5.

From the evader's point of view there would have existed approximately one two minute interval a year during which a magnitude 5.0 clandestine explosion could have been fired in the Kuriles with minimum risk of detection by LASA. From the detector's point of view, there would have been approximately 30 two minute intervals a year, in the codas of Kurile earthquakes, which would have to have been searched for a clandestine explosion of magnitude 5.0. Of these latter intervals there would have been approximately

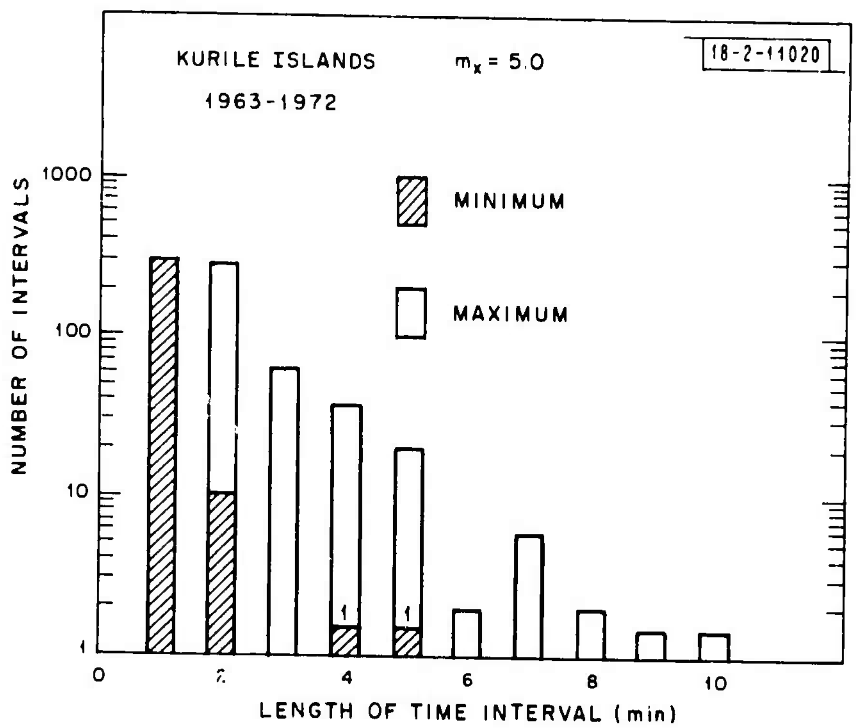

Fig. 13. Estimates of the number of separate time intervals of a given length that a hypothetical magnitude 5.0 explosion in the Kurile Islands would have gone undetected at LASA due to the seismicity of the Kurile Islands during the decade 1963-1972. The hollow bars represent the maximum number of intervals during which the explosion might possibly have gone undetected, based on the maximum number of missed detections at LASA. The shaded bars represent the number of intervals that the explosion most probably would have gone undetected at LASA, based on a minimum number of missed detections at LASA.

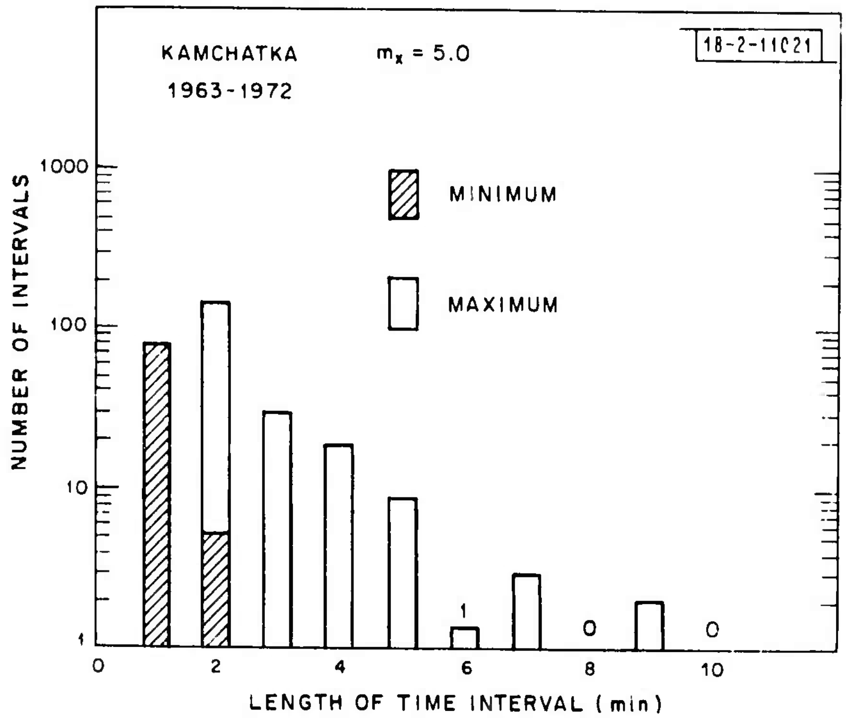

Fig. 14. A diagram analogous to Fig. 14 showing the estimates of the number of separate time intervals of a given length that a hypothetical magnitude 5.0 explosion on the Kamchatka Peninsula would have gone undetected at LASA due to the seismicity of the Kamchatka region during the decade 1963-1972.

one where no positive determination, of whether an explosion had or had not occurred, could be made.

No estimate can be made of the maximum or possible number of one minute intervals because of the condition expressed by equation (5). The number of one minute intervals within which it would have been impossible to determine whether a 5.0 test had occurred or not is approximately 300 for the Kurile Islands and 80 for the Kamchatka region. It is pointed out that the P wave travel time across these regions is approximately two minutes.

CONCLUSION

A method has been developed which yields an extimate of the maximum total time, during a specific period of time at a seismic station, that earthquakes in a given region will mask the detection of a second event, here taken to be an explosion, from another region. The maximum mask time is given as a function of explosion magnitude in each of four cases. In two of these cases the explosion site was taken to be in central Asia while the interferring earthquakes came from the Kurile Islands and the Kamchatka Peninsula. In the two other cases the earthquakes and explosions were collocated in the Kuriles and near Kamchatka. The total mask time at LASA in the first two cases was found to be about an order of magnitude less than the latter two. In these latter cases, it was found that a magnitude 5.5 explosion in the Kuriles would have gone undetected for a maximum total time of about 33 hours due to Kurile Islands seismicity during the decade 1963-1972. The same explosion on Kamchatka would have been masked for a maximum total of about 17 hours during the same period due to the Kamchatka region seismicity.

The results of these experiments are discussed in the light of a scheme which would attempt to evade detection of a clandestine explosion by firing just after an earthquake. In such a discussion it is important to not only know the total amount of time available for such a ruse but also how this time is quantified and what the risks of detection are for certain earthquake-explosion magnitude differences. It was found that due to Kurile Islands earthquakes during the decade there were a maximum of approximately 300 two minute intervals within which a magnitude 5.0 explosion in the Kuriles might possibly have gone undetected at LASA. During approximately ten of these intervals the explosion surely would have gone undetected at LASA due to Kurile Islands seismicity.

The respective number of two minute intervals for the same explosion collocated with earthquakes in the Kamchatka region are approximately 130 and 5.

The numbers presented in this paper should not be considered as definitive since they are based on a rather crude detection scheme applied at only one array. More sophisticated detection schemes applied simultaneously at a network of stations or arrays should lower these estimates. The method of estimating the total mask time however may have general applicability.

ACKNOWLEDGEMENT

I am grateful to Dr. R. T. Lacoss for discussions of various aspects of this work. The responsibility for the conclusions reached through these discussions lies entirely with the author.

REFERENCES

1. Anonymous, "Seismic Array Design Handbook", Federal Systems Division, International Business Machines (August 1972).

APPENDIX

List of Earthquakes

No.	Date Mo.	day	yr.	Origin Time Hr.	min.	sec.	Latitude °North	Longitude °East	Depth km	Magnitude m_b
							Kurile Islands			
1	1	2	68	7	30	11.7	45.7	150.9	87	4.7
2	1	8	68	13	50	42.0	49.1	151.3	284	5.0
3	1	11	68	18	8	38.1	46.4	153.3	50	4.7
4	1	29	63	10	19	5.6	43.6	146.7	40	6.3*
5	1	29	68	10	42	8.6	43.2	147.2	41	5.2
6	1	29	68	11	25	24.1	43.6	147.2	33	4.4
7	1	29	68	11	43	59.1	43.4	147.3	33	5.1
8	1	29	68	12	7	8.0	43.2	147.3	33	5.0
9	1	29	68	14	43	50.5	43.1	146.9	33	4.7
10	2	1	68	12	47	23.4	43.2	146.9	35	5.5
11	2	4	68	9	10	25.3	43.2	147.2	33	5.4
12	2	4	68	11	0	50.1	43.0	147.1	33	5.5
13	2	4	68	11	6	21.0	43.1	147.0	35	5.3
14	2	5	68	6	12	49.8	43.1	146.9	25	4.6
15	2	7	68	12	15	17.3	43.0	146.8	42	4.6
16	2	8	68	12	4	12.8	43.2	147.2	45	5.0

No.	Date Mo.	day	yr.	Origin Time Hr.	min.	sec.	Latitude °North	Longitude °East	Depth km	Magnitude m_b
						Kamchatka Region				
17	1	8	67	8	32	4.4	56.1	162.9	61	4.9
18	2	1	67	9	18	51.5	55.6	160.7	151	4.4
19	2	7	67	19	40	17.2	55.4	162.8	58	4.9
20	8	22	67	6	25	17.8	52.6	159.3	33	4.3
21	9	4	67	[illegible]	30	13.7	54.8	159.1	182	4.6
22	10	9	67	14	10	57.4	54.1	155.1	393	5.2
23	10	10	67	19	8	53.5	55.7	164.4	33	4.6
24	12	16	67	20	53	58.3	51.2	157.7	24	5.5
25	1	3	68	7	49	4.0	54.9	161.5	39	4.8
26	2	29	68	15	46	18.2	52.8	157.5	151	5.4
27	4	15	68	17	25	7.8	53.5	159.7	33	4.7
28	8	22	68	20	39	51.3	55.0	165.8	47	5.0
29	8	30	68	5	24	41.6	51.3	157.7	21	5.1
30	9	12	68	11	43	58.1	51.0	161.7	33	4.6
31	1	20	69	14	20	11.5	54.9	166.0	23	6.1
32	4	4	69	23	57	16.8	[illegible].4	169.4	27	5.4
33	7	16	69	8	16	53.3	52.3	159.0	69	5.8
34	10	12	69	14	22	11.6	55.2	161.9	69	4.6

* m_b taken from the Bulletin of the International Seismological Centre.